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LIQUID SODIUM AS A HEAT TRANSFER
MEDIUM AT HIGH TEMPERATURES

by

Edward Everett Conrad,
Commander, United States Navy

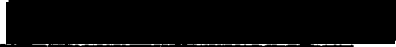
Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE

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Paul J. Kiefer
Chairman
Department of Mechanical Engineering

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Academic Dean (*acting*)

PREFACE

The work done in drawing up this thesis was done at the General Electric Company in Schenectady, New York, from February to May, 1949. It was done in order to evaluate the feasibility of using a liquid metal heat transfer medium at elevated temperatures. The writer's interest along these lines was aroused by the engineers of the General Engineering and Consulting Laboratory of General Electric Company. These engineers have the problem of extracting heat from a prime heat source at high temperatures and are in search of the most effective method of accomplishing this.

Appreciation is expressed to Professor Harold A. Johnson, on leave from the University of California, for guidance and assistance in this thesis. Professor Johnson is at present doing heat transfer work for the General Electric Company. Appreciation is also expressed to the many engineers of the General Electric Company who have offered assistance in this undertaking.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area for heat transfer.
C_p	Specific heat.
D	Inside diameter of coolant passage.
f	Friction factor, $.046/(Re)^{.2}$.
G	Mass velocity of coolant, $u\rho$.
g	Acceleration due to gravity.
h	Heat transfer coefficient.
J	Work conversion factor.
k	Thermal conductivity.
L	Length of coolant passage in heat source.
n	Number of coolant passages of diameter D and length L.
Nu	Nusselt Number, hD/k .
ΔP	Pressure drop of coolant across heat source.
Pr	Prandtl Number, $C_p\mu/k$.
Q	Rate of heat removal.
Re	Reynolds Number, $Du\rho/\mu$.
T	Temperature.
ΔT	Temperature rise of coolant across heat source.
Δt	Average temperature difference between wall of heat transfer passage and bulk temperature of coolant.
U	Overall heat transfer coefficient.
u	Average velocity of coolant in heat source passage.
V_c	Volumetric flow rate of coolant.
V_m	Volume of metal in tube wall.
V_h	Volume of coolant in passage of heat source.
V_t	Total volume of tube metal and coolant in tube.

W Work required for pumping the coolant.

w Mass rate of flow of coolant.

Greek

β Coefficient of cubical expansion.

Δ Tube wall thickness.

μ Viscosity of coolant.

ρ Density.

σ Surface tension.

I. INTRODUCTION

The need for a method of heat transfer at high temperatures has arisen, which need calls for new engineering techniques not previously used. One of the techniques which must be mastered before this proposed heat transfer can be effected is the efficient use of a suitable heat transfer medium at elevated temperatures.

In the past, the conventional method of converting heat into useful work consisted of generating steam in an oil or coal fired boiler and routing the steam to a turbine where it could be converted into useful work.

With a heat source of the order of 1000°F, it is necessary to consider media other than steam to carry the heat away from the heat source. In this thesis, I propose to investigate sodium as a heat transfer medium at high temperatures and to arrive at a conclusion as to its feasibility for this use. Limitations in its use will be discussed and weighed for their relative restrictive powers.

II. GENERAL CONSIDERATIONS

When we suggest sodium as a possible liquid metal for use in the removal of high temperature heat, we immediately think of the many dangers which are inherent in the handling of the metal. It reacts so violently with water that it is a menace to any personnel who might be in the vicinity. This hazard must be overcome by making the system enclosing the sodium absolutely leak proof. This is a major achievement in itself. A closed system can be made leak proof with a fair degree of reliability if there are no moving parts, but with moving parts the probability of leaks increases rapidly as the number of moving parts increases.

Let us regard the circulation problem for sodium. In the past, some experience has been gained in moving sodium in piping systems by means of a pressure exerted by an inert gas, such as argon. Such a method is satisfactory in a system that is not entirely filled with sodium and in which a supply of gas can be provided to move the liquid sodium in one direction. But in a recirculating system such as would be necessary in this case, we would have to provide a pump which could continuously recirculate the sodium in the closed loop. As I see the problem, there are two possibilities for such a pump, namely, a mechanical pump or an electromagnetic pump.

If we use a mechanical pump in our system, we shall have moving parts which will present opportunities for leaks to develop. A mechanical pump has not been manufactured which is leak proof, and if one were devised that were tight, there would always exist the possibility that a leak would develop in the packing. An effective seal for a mechanical rotating shaft pump is the bellows-type eccentric drive. A sketch for

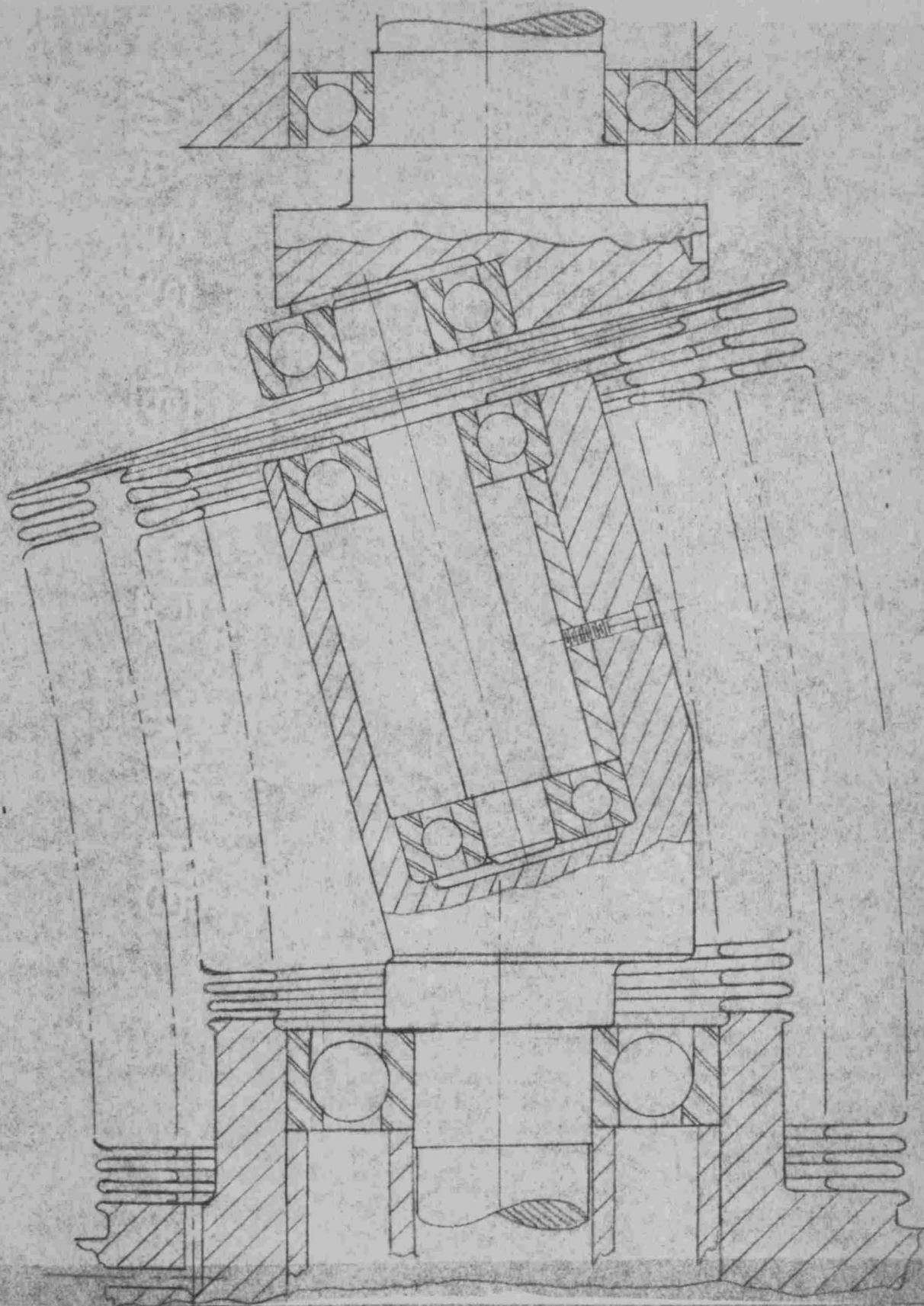


Figure 1. Bellows Type Eccentric Drive.

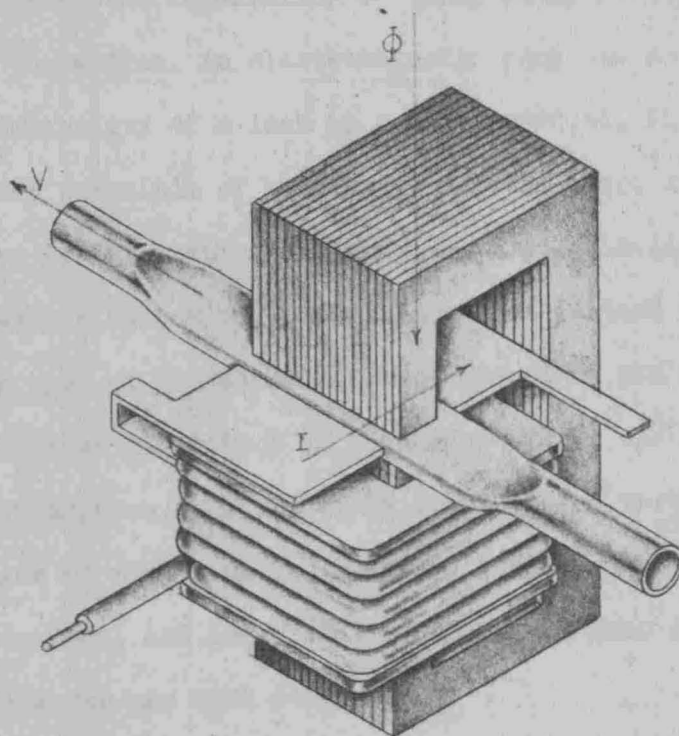


Figure 2. Electromagnetic Pump

Liquid metal (conductor of electricity) will flow in pump conduit due to electric current and a magnetic field angularly disposed to each other and to the direction of flow of liquid metal. Directions of current, flux, and liquid metal are indicated by arrows in sketch.

such a type of drive is shown in Figure 1. If such a drive were used in the sodium pump, it would always be subject to a rupture in the bellows caused by continuous flexing. A rupture would allow sodium to escape from the pump and the hazard of a sodium fire would exist.

In order to circumvent the possibility of a leak from a mechanical pump, let us consider the feasibility of using an electromagnetic pump for circulating the sodium. An electromagnetic pump has no moving parts and hence the possibility of a leak is greatly reduced. Figure 2 illustrates the general principle of an electromagnetic pump. A limitation of this type of pump is the pumping capacity. Perhaps this limitation could be reduced by using a number of loops in parallel instead of a single loop, and having each of the parallel loops pumped by its own electromagnetic pump. Another limitation is high currents in the range of several thousands of amperes, and extremely low voltages in the range of one volt. The lack of moving parts, however, greatly outweighs the small capacity, high current, and low voltage, and such a pump I consider to be highly feasible for use with sodium.

Now let us take a brief look at the properties of liquid sodium as shown in Table 1.

It is noted that the melting point of sodium is 208°F. and the boiling point is 1621°F. Such temperatures will allow the metal to remain in the liquid state in a high temperature system without the application of pressure. To maintain the heat transfer medium in a single phase during operation of the system is a decided advantage. When the plant is shut down, however, the system must be drained of all sodium so that it will not cause damage when it freezes and expands. It could be drained into a suitable freeze tank when the plant is shut down.

In order to recharge the system, the sodium must be melted to the

Table 1. Physical Properties of Liquid Sodium.

T °F	Density lb/ft ³	Viscosity lb/ft hr	Thermal Cond. BTU/ft ² hr°F/ft	Spec.Heat BTU/lb °F
300	57.2	1.32	47.2	.331
400	56.3	1.07	45.5	.335
500	55.5	.91	44.0	.339
600	54.6	.80	43.1	.342
700	53.8	.71	42.1	.344
800	53.0	.65	41.4	.347
900	52.1	.59	40.9	.349
1000	51.3	.55	40.5	.351
1100	50.5			.353

T °F	Surf.Tension lb/ft	Coef.of Cub.Exp. °F ⁻¹
300	140 x 10 ⁻⁴	143 x 10 ⁻⁶
400	138 x 10 ⁻⁴	146 x 10 ⁻⁶
500	136 x 10 ⁻⁴	149 x 10 ⁻⁶
600	135 x 10 ⁻⁴	152 x 10 ⁻⁶
700	133 x 10 ⁻⁴	154 x 10 ⁻⁶
800	131 x 10 ⁻⁴	156 x 10 ⁻⁶
900	129 x 10 ⁻⁴	158 x 10 ⁻⁶
1000	128 x 10 ⁻⁴	161 x 10 ⁻⁶

Melting Point 208°F
Boiling Point 1621°F

liquid phase and then pumped into the system. Preparatory to starting up the prime heat source, the liquid sodium should be heated in the piping by means of heaters surrounding the pipes and circulated by the pump. This will prevent freezing. After the prime heat source has been cut in the danger of freezing will have been eliminated.

The low viscosity of the liquid metal makes for ease in pumping, resulting in relatively low pumping loads. At the temperatures considered pumping should present no problem from a viscosity point of view.

The density of liquid sodium is such that no severe weight stresses would be placed on the containing system by the enclosed metal, since the density of sodium is less than that of water.

In general, the following factors should be considered in removing heat from a heat source:

- (1) Minimum power consumption for circulating the coolant.
- (2) Minimum volume for heat removal.
- (3) Corrosion of the coolant container by the coolant.
- (4) Temperature level.
- (5) Thermal stability for the coolant.

The above factors will be considered in the succeeding chapters and comparisons will be made between sodium and other possible heat transfer media.

III. PUMPING POWER

Let us assume that the power required for pumping the liquid metal through the heat source can be computed by the following equation:

$$W = \frac{V_c \Delta P}{J} \quad (1)$$

The above equation is valid for media which are incompressible during the passage through the heat source.

For turbulent flow, the pressure drop can be calculated by Fanning's equation:

$$\Delta P = \frac{2fLu^2}{gD} \quad (2)$$

The coefficient of friction, f , is plotted as a function of Reynold's number in Figure 3. The pressure drop arrived at in Equation (2) is the pressure drop due to flow through the tube of the exchanger. In addition to this drop there are also entering and leaving losses in fluid energy which cause a further pressure drop. In general this pressure drop due to entering and leaving losses is,

$$\Delta P = \sum k \left(\frac{\rho u^2}{2g} \right) \quad (3)$$

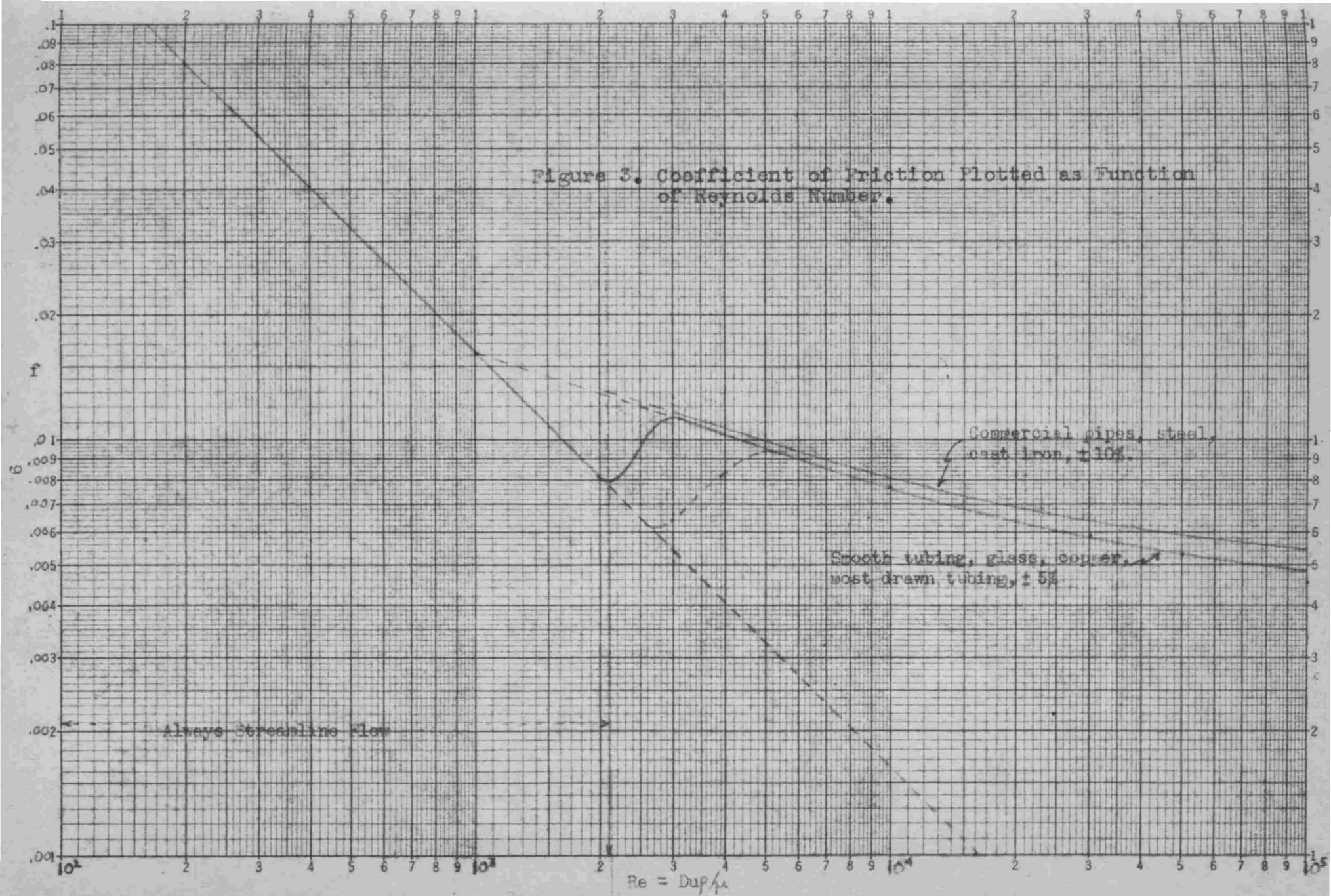
where k is a constant. Hence we get for the total pressure drop,

$$\begin{aligned} (\Delta P)_{\text{total}} &= 4f \left(\frac{L}{D} \right) \left(\frac{\rho u^2}{2g} \right) + \sum k \left(\frac{\rho u^2}{2g} \right) \\ &= (c + \sum k) \left(\frac{\rho u^2}{2g} \right) \end{aligned} \quad (4)$$

or

$$\Delta P \sim \frac{\rho u^2}{2g} \sim u^2$$

Figure 3. Coefficient of Friction Plotted as Function of Reynolds Number.



$$u = \frac{w}{\rho A} = \frac{q}{\rho A C_p \Delta T} \sim \frac{q}{\rho C_p (\Delta T)}$$

since we can consider the area, A, as a constant.

$$\Delta P \sim \rho u^2 \sim \frac{q^2}{C_p^2 \rho (\Delta T)^2} \quad (5)$$

For laminar flow, the pressure drop across the tube can be calculated by Poiseuille's Law:

$$\Delta P = \frac{32 L u \mu}{g D^4} \quad (6)$$

Since we shall generally encounter Reynold's numbers greater than 2000 we shall be primarily interested in the equations for turbulent flow.

A heat balance at the heat source can be set up by the following equation:

$$Q = w C_p \Delta T = V_c \rho C_p \Delta T \quad (7)$$

Equation (7) accounts for the heat rate of the coolant in passing through the tubes with a temperature increase ΔT . Equation (8) accounts for the heat rate in the tube wall.

$$Q = h A \Delta t = h n \pi D L \Delta t \quad (8)$$

From McAdams' Heat Transmission, we can evaluate h as follows for flow inside circular tubes:

$$h = 0.023 \frac{(DG)^{0.8} (Pr)^{0.4} (k)}{(\mu) (D)} \quad (9)$$

For turbulent flow, we can solve for the dimensionless, W/Q , by combining the above equations. This ratio becomes,

$$\frac{W}{Q} = \left(\frac{1}{Jg} \right) \left(\frac{Q^2 L^8}{V_h^2 \Delta T^2 \Delta t} \right) \left(\frac{\mu}{C_p^2 \rho^2 k Pr^{0.4}} \right) \quad (10)$$

In using the equations, average values of physical constants should be used. For example, the temperature of the coolant at the prime heat source and at the coolant pump will be quite different and hence these physical constants should be averaged to cover the range of temperatures and pressures in the system.

Equation (10) gives the value of the ratio of pumping power to heat transferred. The smaller the value of the ratio W/Q , the better the system as regards effectiveness of heat transfer and ease of circulation of the coolant. This dimensionless ratio, therefore, is very useful in evaluating the feasibility of a coolant under specified conditions.

The right hand side of Equation (10) is divided into three brackets. The first bracket is a constant. The second bracket contains those variables which are the dimensions of the system and the conditions under which the system is operating. The third bracket is made up of the physical constants of the heat transfer medium. Let us call this third bracket the physical property group. By looking at Equation (10) it is easy to see that the smaller the physical constant group for any given coolant the better will that coolant be as regards pumping power.

In Table 2 are listed the physical property groups of water and several liquid metals.

It is noted that under turbulent flow conditions sodium has a lower physical property group than all other liquid metals listed. Only water has a lower physical property group. Inasmuch as the data on the physical properties of the liquid metals are not too reliable, the values of

Table 2. Physical Property Groups under turbulent flow conditions of water and several liquid metals.

Liquid	$\frac{\mu}{C_p \rho^2 k \text{Pr}^{0.4}} = x$	$\frac{x}{x_{\text{H}_2\text{O}}}$
H ₂ O	.0004425	1.0
Na	.000877	2.0
Sn	.00157	3.5
Hg	.00335	7.6
Bi	.0053	12.0
Cd	.00583	13.2
Pb	.00787	17.8

the physical property groups are not exactly correct. Temperatures used are all above melting points, but properties for a given coolant are not all referred to a specified temperature. Although the values of physical property groups given are not too accurate, their relative orders of magnitude are fairly reliable, so that some weight can be placed on the smallness of the physical property group of sodium as compared with the other liquid metals listed. This gives an indication of the low pumping power required for sodium as compared with the other liquid metals.

From the relationship given in Equation (10) we see that W is inversely proportional to V_h^2 , $\Delta T^{1.5}$, and $\Delta t^{1.5}$. It is directly proportional to L^2 . It is desirable to have low values of W and V_h , but inasmuch as these two quantities work against each other in the equation (when one becomes small the other becomes large) we must resolve upon a compromise between them. This is the task of the designer when he decides upon the volume to be occupied by the coolant in the heat source. The three values which can be altered to give low values of W and V_h are the length of the coolant passages, L , the temperature difference, ΔT , of the coolant as it enters and leaves the heat source, and the temperature difference, Δt , between the coolant inside tube wall temperature and outside tube wall temperature. The heat transfer designer has direct control over the value of L , but the values of ΔT and Δt are only remotely under his control. ΔT is determined by the temperature level of the heat source and by the amount of energy that is removed from the coolant by the power conversion machinery. The value of Δt is determined by the size and material of the tubes through which the coolant flows.

All other variables being known, the value of L can be determined once the ratio of W/D has been set. When L has been determined, the

value of D can be determined from the following equation for turbulent flow conditions:

$$D^{1.2} = 0.092 \frac{(V_h^{0.2} L^{0.8} \Delta t k^{0.2})}{(Q^{0.2} \Delta T^{0.8} Pr^{0.4})} \quad (11)$$

Or the number of coolant passages may be computed as follows for turbulent flow conditions:

$$n = 68.15 \frac{(V_h^2 Q \Delta T^4 Pr^2)^{1/3}}{(L^3 \Delta t^5 k)} \quad (12)$$

In general, the pumping power is proportional to the volumetric flow rate of the liquid being pumped and the pressure drop in the liquid.

$$\begin{aligned} PHP &\sim \frac{(ft^3)}{(hr)} \frac{(lb)}{(ft^2)} \sim \frac{(w)}{(\rho)} (\Delta P) \\ &\sim \frac{(q)}{(C_p \Delta T)} \frac{1}{\rho} \frac{(q^2)}{(C_p^2 \rho (\Delta T)^2)} \sim \frac{q^3}{C_p^3 \rho^2 (\Delta T)^3} \end{aligned} \quad (13)$$

If we consider the heat rate and temperature drop as being constant we can compare the pumping powers required for different fluids on the following basis:

$$\frac{(PHP)_1}{(PHP)_2} = \frac{C_{p2}^3 \rho_2^2}{C_{p1}^3 \rho_1^2} = (C_{p2}/C_{p1})^3 (\rho_2/\rho_1)^2 \quad (14)$$

Using the above equation as a means of comparing coolants we obtain values of pumping horse powers relative to sodium for various coolants as shown in Table 3. Glancing at this table gives one the impression that sodium is an efficient pumping fluid, requiring little pumping power in comparison with some of the other media listed.

The values of the pumping horse powers required for helium and air are somewhat misleading. The figures listed in Table 3 are for all of

Table 3. Pumping powers required for various heat transfer media as compared with sodium.

Medium	C_p	ρ	C_{pNa}/C_p	ρ_{Na}/ρ	$(C_{pNa}/C_p)^3$	$(\rho_{Na}/\rho)^2$	PHP
Na	.32	.97					1
K	.217	.87	1.47	1.11	3.18	1.23	3.9
Sn	.0577	7.3	5.54	.133	171	.0178	3.05
Hg	.0321	13.6	10.0	.0712	1000	.00508	5.2
Pb	.0297	11.34	10.8	.0855	1260	.00731	9.2
Bi	.0294	9.78	10.9	.099	1300	.0098	12.75
Air(10A)	.2377	.00408	1.344	237	2.43	56,200	58,000
He (10A)	1.25	.000565	.256	1720	.0168	2,960,000	26,500

the heat transfer media passing through tubes of equal diameters and equal lengths. The pumping horse powers for air and helium could be greatly reduced by using more and larger tubes than we would use for a liquid metal. Therefore, the comparative values of sodium and air or helium are not quite valid as shown in Table 3. We would find it feasible to use air or helium only if these media occupied a large volume in the prime heat source, but if the volume is to be small we must use a liquid coolant in order to keep low pumping powers.

IV. VOLUMETRIC AND VELOCITY CONSIDERATIONS

1. Design Equations.

Let us assume a power plant with an output of 8,000 SHP and a thermal efficiency of 25%. Such a plant would require a heat input at the prime heat source of

$$(8000/.25 \text{ HP})(33000 \times 60 \text{ ft.lb/HP-hr})(1.286 \times 10^{-3} \text{ BTU/ft.lb}) = 8.14 \times 10^7 \text{ B/hr}$$

Let us further assume the following:

Sodium will be circulated through the prime heat source in type 347 stainless circular tubes whose wall thickness will be proportional to the diameter. This ratio of wall thickness to diameter will be 0.08. The heat transfer tubes will be distributed in such a way that each tube receives heat at the same rate.

The coolant tubes will be straight tubes arranged in parallel.

We shall select three independent variables: L , the length of the tube; u , the velocity of the sodium in the tube; ΔT , the temperature rise of the sodium in passing through the heat source.

For turbulent flow conditions:

$$Q = wC_p \Delta T = V_c \rho C_p \Delta T \quad (15)$$

$$Q = hA \Delta T = h n \pi D L \Delta T \quad (16)$$

$$h = 0.004(DG/\mu)^{0.8}(\text{Pr})^{0.4}(k/D) \quad * \quad (17)$$

$$V_c = (n \pi D^2 L / 4)(u/L) = n \pi D^2 u / 4 \text{ ft}^3/\text{sec} \quad (18)$$

$$\text{Pr} = C_p \mu / k, \quad G = u \rho$$

* The constant, 0.004, is based on Martinelli's curves, Figure 4, and differs from McAdams' constant, 0.023, in Equation (9).

Combining Equations (15), (16) and (17) we get,

$$V_c C_p \rho \Delta T = 0.004 (DG/\mu)^8 (Pr)^4 (k/D) n \pi D L \Delta T \quad (19)$$

Combining Equations (18) and (19),

$$(n \pi D^2 u / 4) C_p \rho \Delta T = 0.004 (Du \rho / \mu)^8 (C_p \mu / k)^4 (k/D) n \pi D L \Delta T \quad (20)$$

$$L/D^{1.2} = \frac{(u)^2 (\rho)^2 (C_p)^6 (\mu)^4}{.016 (k)^6} \quad (21)$$

Substituting the values of the physical constants of sodium, lead, and helium in Equation (21), we arrive at the following relationships for L, D, and u:

$$\text{Sodium:} \quad L/D^{1.2} = 5.75(u)^2$$

$$\text{Lead:} \quad L/D^{1.2} = 9.55(u)^2$$

$$\text{Helium:} \quad L/D^{1.2} = 37.5(u)^2$$

From the above three equations for sodium, lead, and helium, we observe that the length of the sodium tubes will be much shorter than for lead and helium for the same tube diameter and coolant velocity. This is a decided advantage for sodium from a design point of view.

2. Volumetric Equations.

$$V_h = n \pi D^2 L / 4 \quad (22)$$

Combining Equations (15), (18), and (22),

$$V_h = V_c L / u = Q L / C_p \rho \Delta T u \quad (23)$$

Using a value of Q equal to 8.14×10^7 BTU/hr, and using the physical constants for sodium, lead, and helium, we arrive at the following values of V_h for the three media mentioned:

$$\text{Sodium:} \quad V_h = 4.88 \times 10^6 \text{ (L/u}\Delta T\text{)}$$

$$\text{Lead:} \quad V_h = 3.8 \times 10^6 \text{ (L/u}\Delta T\text{)}$$

$$\text{Helium:} \quad V_h = 1640 \times 10^6 \text{ (L/u}\Delta T\text{)}$$

From these three equations we observe that sodium and lead have volumes of the same order of magnitude for the same values of L , u , and T . Helium, on the other hand, requires roughly four hundred times as much volume for coolant in the prime heat source as does sodium.

The amount of metal in the coolant tube walls will be directly proportional to the amount of coolant in the tubes. This is apparent from the following set of equations:

$$\Delta = .08D$$

$$D_o = D + 2\Delta = D + 2 \times .08D = D + .16D = 1.16D$$

$$V_t = \pi(D_o)^2 L / 4 = (1.16)^2 \pi D^2 L / 4 = 1.346V_h$$

$$V_m = V_t - V_h = 1.346V_h - V_h = .346V_h \quad (24)$$

3. Velocity Equations.

Solving for u in Equation (23), we get:

$$u = (Q/c_p \rho) (L/V_h \Delta T) \quad (25)$$

Substituting the value of V_h from Equation (22) in Equation (25) gives

$$u = (Q/C_p \rho) (4/n\pi D^2 \Delta T) \quad (26)$$

Let us assume that $n = 200$, $D = 1" = 1/12'$, $\Delta T = 250^\circ\text{F}$. Using the particular physical constants for C_p and ρ , and using a value of Q as given previously, we get the following results for the velocities of sodium, lead, and helium:

Sodium: $u = 4.97 \text{ ft/sec.}$

Lead: $u = 3.87 \text{ ft/sec.}$

Helium: $u = 1670 \text{ ft/sec.}$

These results are obtained from Equation (26), and from them we observe that lead and sodium are within reasonable limits while helium has a velocity which exceeds the speed of sound. This of course is impossible for helium, and is somewhat misleading. Since a large volume of helium would be needed to carry away the heat from the prime heat source, the volume for the helium should be greater than the volume for sodium under the same conditions. If such were the case the velocity of the helium coolant could be brought within reason. Hence from a velocity point of view, sodium and lead would be suitable if the volumes were fairly small or large, but helium would be suitable only if the volume were large.

V. TEMPERATURE LEVEL

1. Assumptions.

From a heat transfer basis let us consider a system of heat removal from a prime heat source using sodium, lead, mercury, and helium as coolants. We shall assume that the heat transfer medium is flowing through round straight tubes each of which receives heat at equal rates. In addition we shall make the following assumptions:

$$Q = 8.14 \times 10^7 \text{ BTU/hr.}$$

$$L = 2 \text{ ft.}$$

$$n = 200 \text{ tubes.}$$

$$\Delta T = 950 - 700 = 250^\circ\text{F.}$$

$$T_{\text{av}} = (950 + 700)/2 = 825^\circ\text{F.}$$

$$D_i = 1 \text{ in.}$$

$$D_o = 1.16 \text{ in.}$$

Tube wall - Type 347 Stainless.

2. Sodium.

$$Q = wC_p\Delta T \quad (7)$$

$$w = \frac{Q}{C_p\Delta T} = \frac{(8.14 \times 10^7 \text{ B/hr})}{(.32 \text{ B/lb.}^\circ\text{F})(250^\circ\text{F})} = 1.017 \times 10^6 \text{ lb/hr. Total}$$

Through each tube, $w = 1.016 \times 10^6 / 200 = 5.085 \times 10^3 \text{ lb/hr.}$

$$Re = Du\rho/\mu = \frac{(1/12 \text{ ft})(5.085 \times 10^3 \text{ lb/hr})(4 \times 144/\pi \text{ ft}^2)}{(.64 \text{ lb/ft.hr})} = 1.214 \times 10^5$$

$$Pr = C_p\mu/k = \frac{(.32 \text{ B/lb.}^\circ\text{F})(.64 \text{ lb/ft.hr})}{(41.4 \text{ B/hr.ft.}^\circ\text{F})} = 0.00495$$

From curves in Figure 4, we find that for the above values of Re and Pr moduli, the Nu modulus is

$$Nu = hD/k = 11.6$$

$$h(\text{film}) = 11.6 k/D = \frac{11.6 (41.4 \text{ B/hr.ft.}^{\circ}\text{F})}{(1/12 \text{ ft})} = 5780 \text{ B/hr.ft}^2 \text{ }^{\circ}\text{F.}$$

$$\text{In each tube, } q = \frac{\Delta t}{(1/hA_i) + (\Delta/kA_{LM})} \quad (8a)$$

$$A_i = \pi DL = \pi(1/12)^2 = \pi/6 \text{ ft.}^2$$

$$A_{LM} = \frac{A_o - A_i}{\ln A_o/A_i} = \frac{\pi(1.16/12)^2 - \pi/6}{\ln 1.16/1} = .565 \text{ ft.}^2$$

Substituting the known values in Equation (8a) we get:

$$\frac{8.14 \times 10^7}{200} \text{ B/hr} = \frac{\Delta t \text{ }^{\circ}\text{F}}{\frac{1}{(5780 \times \pi/6 \text{ B/hr.}^{\circ}\text{F})} + \frac{.08/12}{(15 \times 1.08 \pi/6 \text{ B/hr.}^{\circ}\text{F})}}$$

$$\Delta t = 412^{\circ}\text{F.}$$

$$T(\text{heat source}) = 825 + 412 = 1237^{\circ}\text{F.}$$

3. Lead.

$$w = \frac{Q}{C_p T} = (8.14 \times 10^7) / (.0374)(250) = .87 \times 10^7 \text{ lb/hr. Total}$$

Through each tube, $w = .435 \times 10^5 \text{ lb/hr.}$

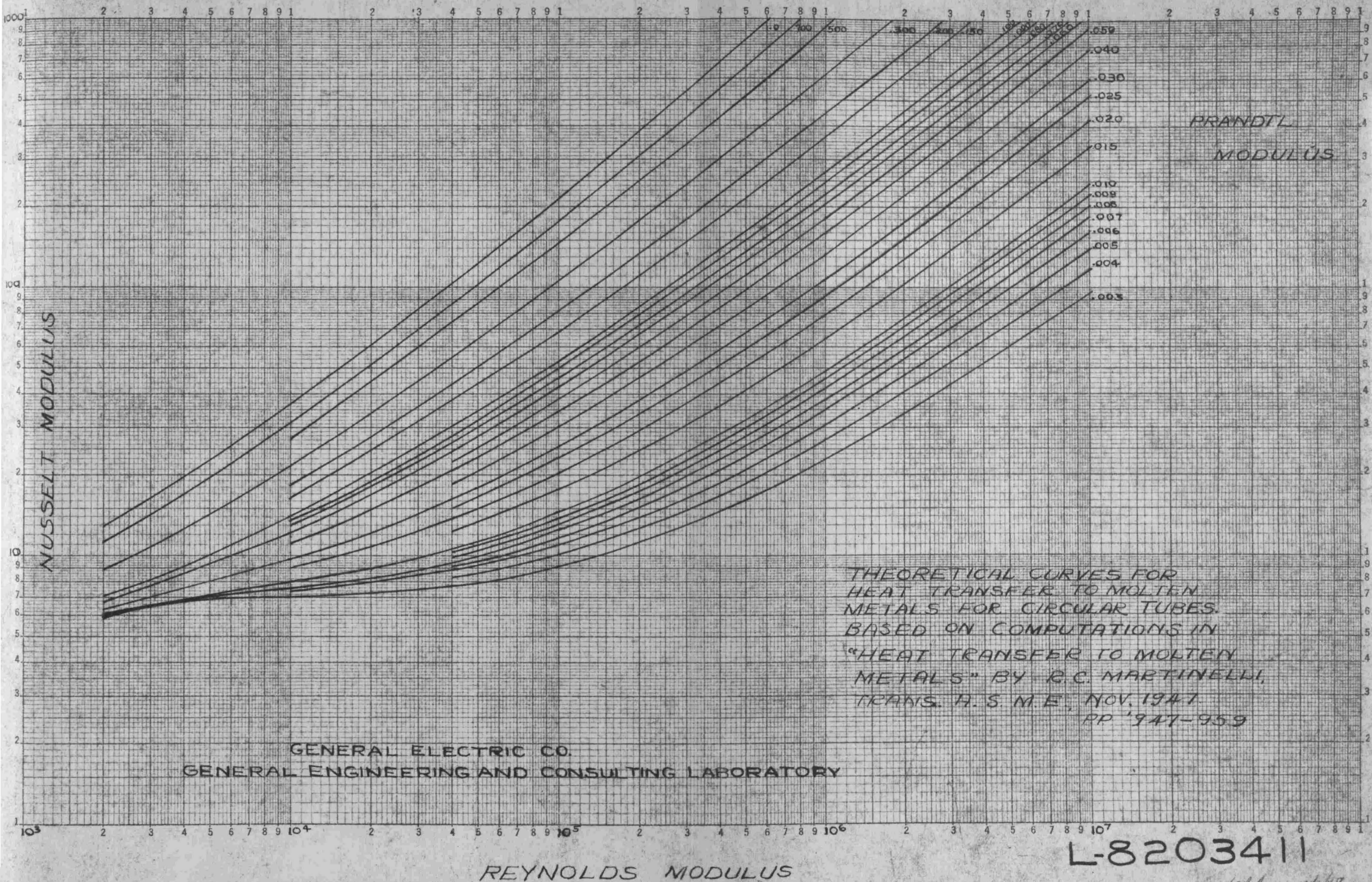
$$Re = D\rho/\mu = \frac{(1/12)(.435 \times 10^5 \times 4 \times 144/\pi)}{(2.1 \times 2.42)} = 4.10 \times 10^5$$

$$Pr = C_p \mu/k = (.0374)(2.1 \times 2.42) / .0384 \times 241.9 = .02045$$

From Figure 4, $Nu = 46.0$

Figure 4. Theoretical Curves for Heat Transfer to Molten Metals
for Circular Tubes.

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$$h = Nu k/D = 46(.0384 \times 241.9)/(1/12) = 5130 \text{ B/hr.ft}^2 \text{ } ^\circ\text{F.}$$

Substituting the known values in Equation (8a), we get:

$$\frac{8.14 \times 10^7}{200} = \frac{\Delta t}{1/(5130\pi/6) + .000786}$$

$$\Delta t = 471^\circ\text{F.}$$

$$T_{(\text{heat source})} = 825 + 471 = 1296^\circ\text{F.}$$

4. Mercury.

$$w = Q/C_p \Delta T = (8.14 \times 10^7)/(.0318)(250) = 1.02 \times 10^7 \text{ lb/hr. Total}$$

$$\text{Through each tube, } w = .51 \times 10^5 \text{ lb/hr.}$$

$$Re = Du\rho/\mu = \frac{(1/12)(.50 \times 10^5 \times 4 \times 144/\pi)}{(2.03)} = 3.84 \times 10^5$$

$$Pr = C_p \mu/k = .00685$$

$$Nu = 23$$

$$h = Nu k/D = 23 \times 9.38/(1/12) = 2590 \text{ B/hr.ft}^2 \text{ } ^\circ\text{F.}$$

Solving Equation (8a), we get:

$$\Delta t = 620^\circ\text{F.}$$

$$T_{(\text{heat source})} = 825 + 620 = 1445^\circ\text{F.}$$

5. Helium.

$$w = Q/C_p \Delta T = (8.14 \times 10^7)/(1.25)(250) = 2.60 \times 10^5 \text{ lb/hr. Total}$$

$$\text{Through each tube, } w = 1.30 \times 10^3 \text{ lb/hr.}$$

$$Re = Du\rho/\mu = \frac{(1/12)(1.30 \times 10^3 \times 4 \times 144/\pi)}{(.033 \times 2.42)} = 2.49 \times 10^5$$

$$Pr = C_p \mu / k = \frac{(1.25)(.033 \times 2.42)}{(64 \times 10^{-5} \times 241.9)} = .644$$

$$Nu = 350$$

$$h = Nu k/D = (350)(64 \times 10^{-5} \times 241.9)/(1/12) = 650 \text{ B/hr.ft}^2 \text{ } ^\circ\text{F.}$$

Substituting the known values in Equation (8a), we get:

$$\frac{8.14 \times 10^7}{200} = \frac{\Delta t}{1/(650 \times \pi/6) + .000786}$$

$$\Delta t = 1510^\circ\text{F.}$$

$$T_{(\text{heat source})} = 825 + 1510 = 2335^\circ\text{F.}$$

6. Comparisons.

As seen in the preceding sections of this chapter, sodium, when used as a heat transfer medium under the same conditions as helium and lead and mercury, will require a lower temperature at the prime heat source. This in turn calls for less heat input in the prime heat source and consequently economy of fuel. To obtain a heat transfer medium outlet temperature of 900°F. , it is necessary that the prime heat source temperature at the tube wall be as follows for the media listed:

Sodium	1237°F
Lead	1296°F
Mercury	1445°F
Helium	2335°F

From the results tabulated above it is observed that sodium has good qualities from a point of view of temperature of the heat source.

VI. PHYSICAL PROPERTIES

1. Density.

Density of liquid sodium may be computed by the following empirical equation:

$$\rho = 0.9514 - 2.392 \times 10^{-4} T \quad (27)$$

where ρ is in gm/cm³, and T is in °C. This equation is reliable to within $\pm \frac{1}{2}\%$ in the temperature range from the melting point of sodium to 700°C.

From the above equation we can compute the coefficient of cubical expansion as:

$$\beta = 2.932 \times 10^{-4} / (0.9514 - 2.392 \times 10^{-4}) \quad (28)$$

The coefficient of cubical expansion for sodium is not too different from that of other well known liquids, i.e., β at 20°C is 2.07×10^{-4} for water and 1.82×10^{-4} for mercury.

The change of volume of sodium on melting is 2.71% at one atmosphere, which is quite normal.

2. Heat Capacity.

The values of heat capacity for sodium at high temperatures are as yet not too firmly established. The values listed in Table 1 are believed to be fairly reliable, but work is being done at the present time at the Bureau of Standards to check and if necessary refine these values.

The specific heat values of the various liquid metals are very important in the determination of their usefulness as heat transfer media. Let us look at the specific heats of several liquids: Lithium (1.407

cal/gm,^oC); Sodium (0.32); Potassium (0.217); Gallium (0.080); Tin (0.057); Indium (0.057); Mercury (0.0321). The above values are at 100^oC.

If we are interested in the maximum amount of heat that can be absorbed per unit volume of the liquid we can make a comparison of the metals on this basis in the following table.

Table 4. Heat Capacity per Unit Volume (cal/cm³,^oC)

Lithium	0.556
Sodium	0.31
Potassium	0.187
Gallium	0.472
Tin	0.423
Indium	0.416
Mercury	0.434

Here we notice not too wide a dispersion of the heat transfer qualities when viewed from a volumetric point of view. Sodium and Potassium have the lowest volumetric values. Gravimetrically considered, sodium is much better than the other materials with the exception of lithium.

3. Surface Tension.

Surface tension for sodium may be computed from the following formula:

$$\sigma = 211.5 - 0.04848(T^{\circ}\text{C}) \text{ dynes/cm.} \quad (29)$$

Values of surface are listed in Table 1.

4. Thermal Conductivity.

The thermal conductivities of sodium have been very difficult to determine over a temperature range. The Naval Research Laboratory is at

the present time engaged in such research. Their values are in fair agreement with the values listed in Table 1. In general the following equation is reliable:

$$k = 0.216 - 1.294 \times 10^{-4}T \quad (30)$$

where k is in $\text{cal/cm}^2, \text{sec}, ^\circ\text{C/cm}$, and T is in $^\circ\text{C}$.

Reliability of Equation (30) is $\pm 0.005 \text{ cal/cm}^2, \text{sec}, ^\circ\text{C/cm}$.

5. Heat Transfer Coefficient.

We are particularly interested in the heat transfer coefficient of sodium in considering the liquid metal as a heat transfer medium. The heat transfer coefficient will in general be determined by the temperature, velocity of the sodium, and the diameter of the pipe containing the sodium. The heat transfer coefficient can be defined by the following equation:

$$Q = hA(T_w - T_l) \quad (31)$$

where T_w is the temperature of the tube wall, and T_l is the temperature of the liquid.

Actually it is difficult to compute " h " from the above equation, and a much more simple method is in the relationships that have been worked out between Reynolds, Prandtl, and Nusselt Numbers. Knowing velocity and diameter and temperature, we can compute Reynolds number, $Re = Du\rho/\mu$. Prandtl number can be computed, $Pr = C_p\mu/k$. With these two numbers as arguments we enter Figure 4 and find the corresponding Nusselt number. With this value known we can compute " h " from $Nu = hD/k$.

The curves plotted in Figure 4 are based on R.C. Martinelli's work and are believed to be reliable.

6. Melting and Boiling Points.

The temperature range over which sodium is liquid is 97.5°C . to 880°C . This is a fairly good temperature range for use in a high temperature heat exchanger but the highness of the melting point can act as a disadvantage. Gallium, for example, has a much better range, extending from 30°C . to 2000°C . Gallium is undoubtedly the best liquid metal coolant when considered from a liquid phase temperature range, but it has some drawbacks. Tin melts at 231.9°C . and boils at 2270°C . The temperature range of the liquid state of tin is thus somewhat wider than for gallium, but the higher melting point of tin, 231.9°C ., makes it undesirable. The metal indium (melting point 155°C ., boiling point 1450°C .) is intermediate between sodium and tin in melting points and boiling points. Its cost, however, is prohibitive, and it is doubtful whether it could be obtained in sufficient quantities to be used in a heat exchanger. Mercury is liquid at room temperature, which is very desirable, but it has a low boiling point, 357°C . The toxic nature of mercury vapor is a further disadvantage of using it as a coolant. Potassium melts at 62.3°C . and boils at 758°C ., which is approximately of the same range as sodium. It, like sodium, is very reactive with water and water vapor, and hence presents a hazard similar to sodium. Lithium melts at 186°C ., and boils at 1609°C , a fairly good range except for the high melting point. Lead melts at 327°C . and boils at 1603°C .

Reviewing the above melting and boiling points, we observe that only two of the materials mentioned have lower melting points than has sodium. These are gallium and potassium (mercury is not included since it is normally in the liquid phase). Availability of sufficient amounts of gallium limit its potentialities and hence it cannot be considered as a serious contender. Potassium is quite similar to sodium and its temperature

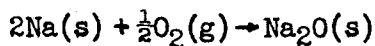
range is favorable. With a melting point of 97.5°C . not too much heat is required to maintain the metal in the liquid phase which is a decided advantage in its use as a heat transfer medium. The boiling point at 880°C . is in the vicinity of the melting point of high temperature metals and hence this is considered to be a safe upper limit for operating temperatures.

VII. CHEMICAL PROPERTIES

Sodium is well known for its great chemical activity. In this chapter we shall consider the activity of sodium with some of the substances with which sodium may come in contact in heat transfer work. These substances which we shall consider are: oxygen, water, and metallic oxides.

1. Sodium and Oxygen.

Oxygen reacts with sodium very readily to form Na_2O in accordance with the following reaction:



The heat and free energy of this reaction are:

$$\Delta H = -94,736 + 20.04T - 6.32 \times 10^{-3}T^2 - 586.6T^{\frac{1}{2}}$$

$$\Delta F = -94,736 - 20.04T \ln T + 6.32 \times 10^{-3}T^2 - 1173.2T^{\frac{1}{2}} + 197.89T$$

Energies are in gram calories, and temperatures in $^{\circ}\text{K}$.

Na_2O is a crystalline powder which has corrosive effects on most alloys. It should be guarded against in a sodium system because of this effect, and if it is present it should be removed from the system by cold traps or filtration. For this reason the sodium system should be evacuated down to a fairly good vacuum (less than 100 microns) before the sodium is admitted.

The vapor pressure of Na_2O has been estimated to be:

$$\log p_{\text{mm}} = 7.755 - 7704/T$$

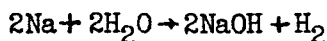
From this equation the normal boiling point of Na_2O is computed to be:

$$T = \frac{7704}{7.755 - \log 760} = \frac{7704}{7.755 - 2.88} = 7704/4.875 = 1580^{\circ}\text{K} = 1307^{\circ}\text{C}.$$

Na_2O , even though it is heavier than sodium, will tend to float on the surface of molten sodium at temperatures below 125°C . Above this temperature, however, the sodium will wet the Na_2O and the latter will sink in the molten sodium, forming a sludge which can be filtered out.

2. Sodium and Water.

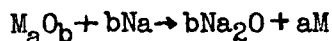
Sodium and water react in accordance with the following equation:



This is quite an explosive reaction. In an inert atmosphere this explosiveness is caused by the rapid generation of hydrogen and steam and the sudden release of heat. If air is present there also exists the rapid reaction of hydrogen and oxygen. Research is being done at the present time by the Naval Research Laboratory on the speeds of these reactions.

3. Sodium and metallic Oxides.

In general, sodium will react with a metallic oxide in accordance with the following equation:



There are many metals whose oxides are reduced by sodium and others which can reduce Na_2O to free sodium. The direction in which the reaction proceeds depends upon whether the free energy of formation of the metallic oxide is greater or less than the free energy of formation of Na_2O .

VIII. CORROSION

Corrosion by sodium is such that it must be considered in designing a sodium system. It has been determined that the corrosion rate of sodium is directly proportional to the oxygen content in the liquid metal. Na_2O will cause corrosion with the possibility of pipe plugging caused by corroded particles. This is extremely undesirable and must be avoided if it is desired to have a system which demands little maintenance attention.

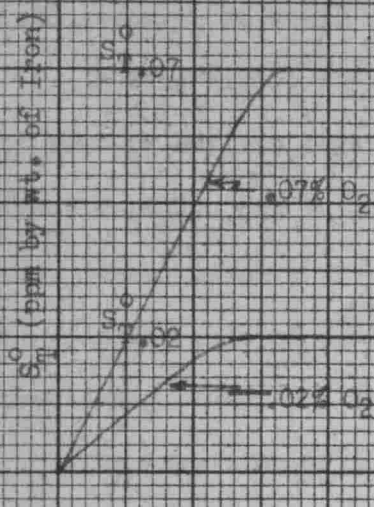
The problem of reducing Na_2O content in sodium must be faced if a sodium coolant is to be used. Oxygen content in sodium can be reduced to approximately .06% by fine filtration. Such degree of purity in sodium will only give fair results in the battle against corrosion. It has been determined that purity in the range of .01% oxygen or less will be needed in order to assure that the sodium system will be free of plugging over a reasonably long operating period. Techniques for preparing sodium of this purity are now being investigated and at the present time it appears that distillation and the use of a "getter" such as calcium are the most effective methods. This is one of the problems which must be solved before sodium can be used as an efficient heat transfer medium.

The corrosion rate of Na_2O on iron is as follows at $500^\circ\text{C}.$:

$$R_{500^\circ\text{C}} = 2 \times 10^{-3} \text{ mg/cm}^2, \text{hr. for sodium which is saturated with oxygen.}$$

In general the corrosion rate follows the curves shown in Figure 5. In this Figure, S_T^0 is the maximum corrosion that will take place at a specified temperature after an elapsed period of time such that no further corrosion will take place with increase in time.

The curves plotted in Figure 6 are the results of dynamic corrosion, i.e., corrosion in which the corroding fluid is in a state of motion past the corroded metal. The results of a static corrosion test for sodium reveal the curve shown in Figure 5.



$T^{\circ}C.$	S_m^0 (ppm by wt.) for .07% O_2
200	4.1
300	7.1
400	10
500	13
600	16
700	18

Figure 5. Static Corrosion curves for Sodium on Iron.

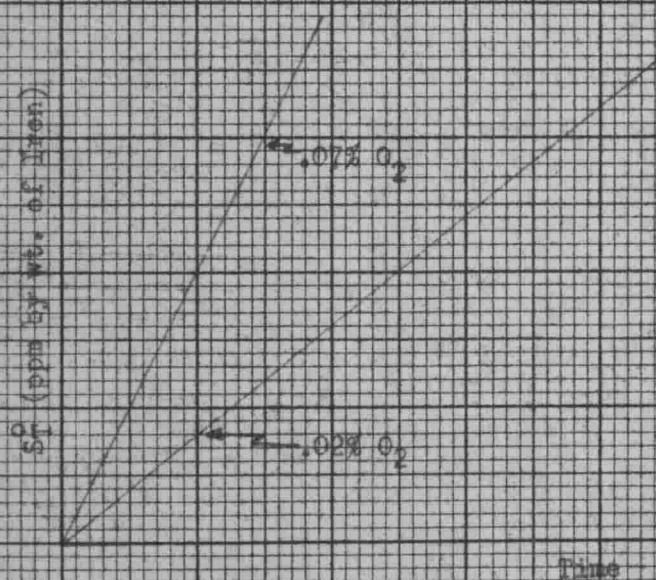


Figure 6. Dynamic Corrosion Curve for Sodium on Iron.

Let us compare the solubility of iron in liquid sodium and in liquid mercury. We shall consider the sketch in Figure 7.

In this Figure we note that the iron atoms are vigorously attacked by mercury surface layer, and that they move from the solid iron to this layer rapidly. But in going from the mercury surface layer to the mercury they travel slowly.

In the case of sodium, these steps are reversed, the iron atoms first travelling slowly and then rapidly into the liquid sodium.

The summation of the two processes we call the solubility, and the first step in each case we call the corrosion. From an analysis of Figure 7, we learn that even though the solubility of iron is greater in sodium than it is in mercury, the corrosion of iron is less in sodium than it is in mercury. This statement appears to be a paradox, but nevertheless is true.

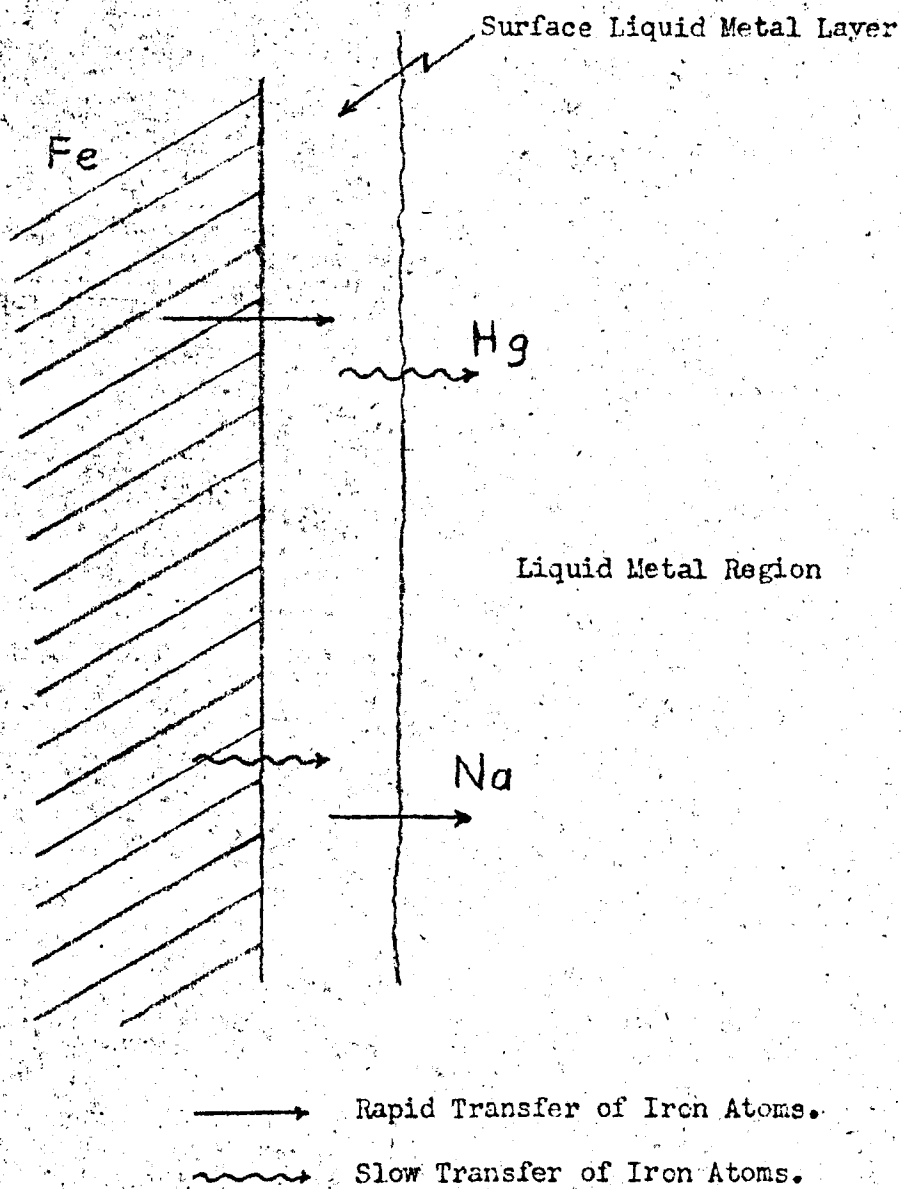


Figure 7. Corrosion and Solubility of Iron in Liquid Sodium and Liquid Mercury.

IX. HANDLING

The handling of sodium is inherently dangerous. The seriousness of the effects of mixing sodium with water are such that all precautions must be taken to prevent water from coming in contact with the sodium. Personnel who are handling sodium must at all times wear protective goggles to guard their eyes from flying sparks from the sodium. Asbestos clothing will protect other parts of the body from ignited sodium.

The safety measures for handling sodium call for the quick availability of sodium fire extinguishers in the event that a sodium fire should start. Smothering has proved to be the most effective means of extinguishing a sodium fire. The smothering material must be dry in order to be effective. Rock dust (CaCO_3) and KCl are both very good for this use and have been very effective in fires which I have observed. Rock dust is conceded to be superior in extinguishing sodium fires. The following comparative results have been obtained, which illustrate the extinguishing properties of KCl and CaCO_3 :

<u>Quantity of</u> <u>Na ignited, lbs.</u>	<u>Dust</u> <u>Used</u>	<u>Propellent</u> <u>Used</u>	<u>Extinguishing</u> <u>Time, min.</u>	<u>Quantity of</u> <u>Dust Used, lbs.</u>
50	KCl	Air	10	420
50	CaCO_3	Air	9.8	360
50	CaCO_3	N_2	6.7	240

Because of its violent explosiveness with water, sodium must be contained in a system which has a very high degree of tightness. Liquid sodium is very penetrating, so that it will find cracks, holes, and passages in walls that are normally resistant to water flow. For this reason all welded joints in the sodium system must be tested for integrity with the mass spectrometer, and imperfect welds must be corrected before the li-

quid metal is admitted. This is a slow and tedious process which must be placed on the check-off list of any sodium system.

When sodium is being stored, it is good practice to place an inert gas above the sodium. Temperature and humidity conditions should be such that sweating on the inside of the container will be prevented. If sweating should occur in the sodium side of the container, the resulting explosion might be disastrous.

The protection against sodium at 350 and 550°C. offered by articles of protective clothing made of the following materials is listed below:

<u>Material</u>	<u>Protection</u>	
	<u>350°C.</u>	<u>550°C.</u>
Leather	Excellent	Excellent
Laminated bakelite	Excellent	Excellent
Rubber	Excellent	None
Lucite	Excellent	None
Wool	None	None
Cotton	None	None

X. CONCLUSIONS

Before stating our decision as to the feasibility of sodium as a heat transfer medium, let us look at the desirable qualities which we consider such a medium should have. These qualities are listed as follows:

1. The heat transfer medium should have a minimum possible volume. Sodium satisfies the volumetric requirement fairly well. Lead would require less volume, and helium would require many times more volume.
2. It should be circulated at a reasonable velocity. Sodium is fair as regards velocity. The velocity of lead is less than that of sodium; that of helium is excessive.
3. There should be low power consumption in pumping. Sodium is excellent insofar as it requires very little pumping power as compared with the other elements. In this respect sodium is outstanding.
4. It should have a high heat transfer coefficient, and high coefficient of thermal conductivity. In both of these qualities, sodium is better than many of the possible heat transfer media, and in general these qualities are considered good for sodium.
5. The temperature of the heat source should not be excessive. This temperature level is lower for sodium than for lead, mercury, and helium.
6. The melting point should not be high, and the boiling point should not be too low. Sodium has a good range of melting point to boiling point. The span is better than for most elements, with the melting point fairly low, 97.5°C .
7. The heat transfer medium must not corrode the materials with which it comes in contact. The corrosion hazard is always present in

sodium and great care must be taken to eliminate this corrosion potential by reducing the amounts of oxygen present in the sodium.

8. It must be at a low pressure. High pressures are not necessary for sodium. Gases must have high pressures unless the volumes are very great.

9. It must be easy to handle. Sodium is difficult to handle, and this is one of its principal drawbacks, together with its explosiveness when mixed with water.

10. It must be available in the required amounts. Availability of sodium is good. DuPont Company is the principal supplier of sodium in the bulk. This product, however, must be purified by one of the processes mentioned before it can be used as a heat transfer medium.

It would be difficult to discover a liquid which would possess all of the above qualities. If such were the case our heat transfer problem would not exist. Since we do not have such a liquid we must select one which possesses good promise as a heat transfer medium.

It is considered feasible to use sodium as a heat transfer medium if proper precautions are taken in its handling. The potential danger which is ever prevalent in sodium is its main disadvantage, and if this disadvantage can be overcome by adequate safety measures, sodium can be a very good heat transfer medium for use at high temperatures. Adequate safety measures are deemed possible.

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